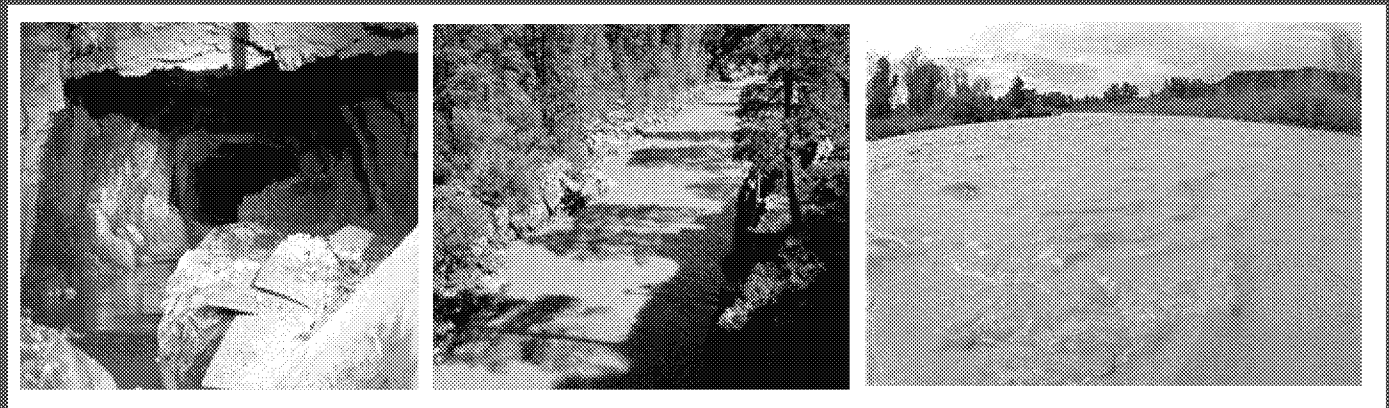


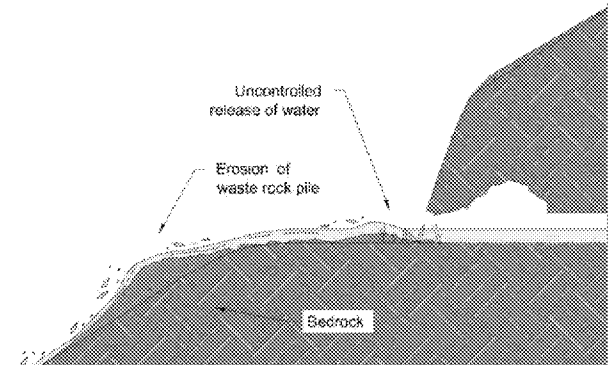
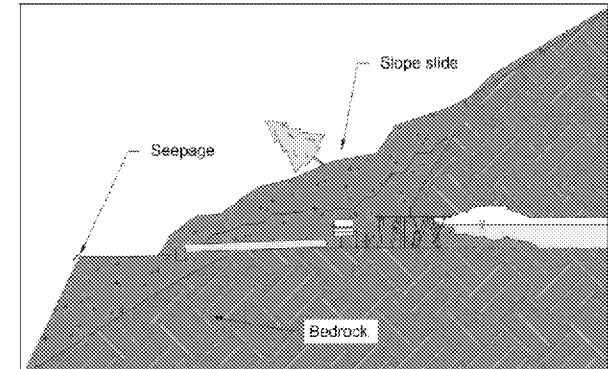
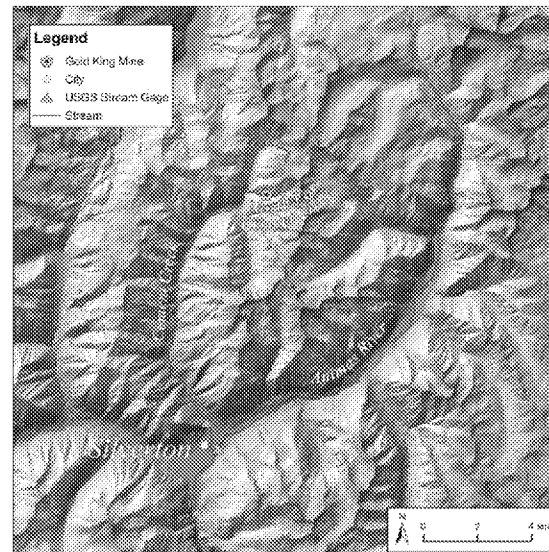
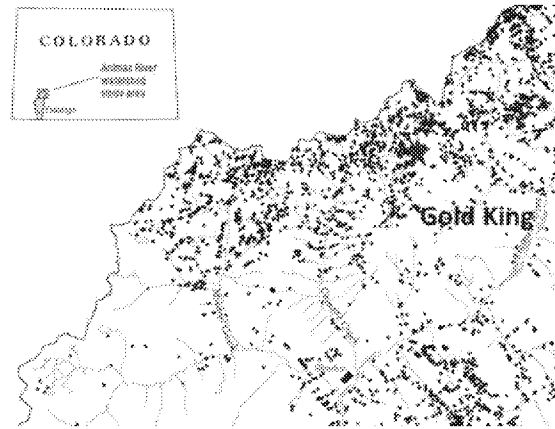
# Characteristics of Metals Concentrations in the Animas and San Juan Rivers During Passage of the Gold King Mine Release Plume

*Kate Sullivan, Mike Cyterski, Chris Knightes, John Washington,  
Steve Kraemer, Lourdes Prieto, Brian Avant*



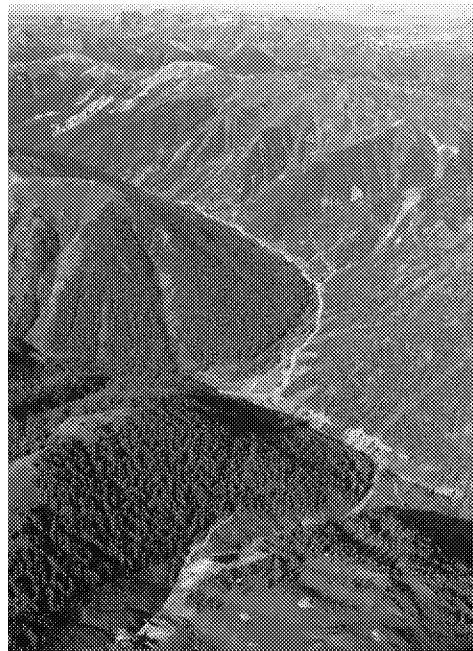
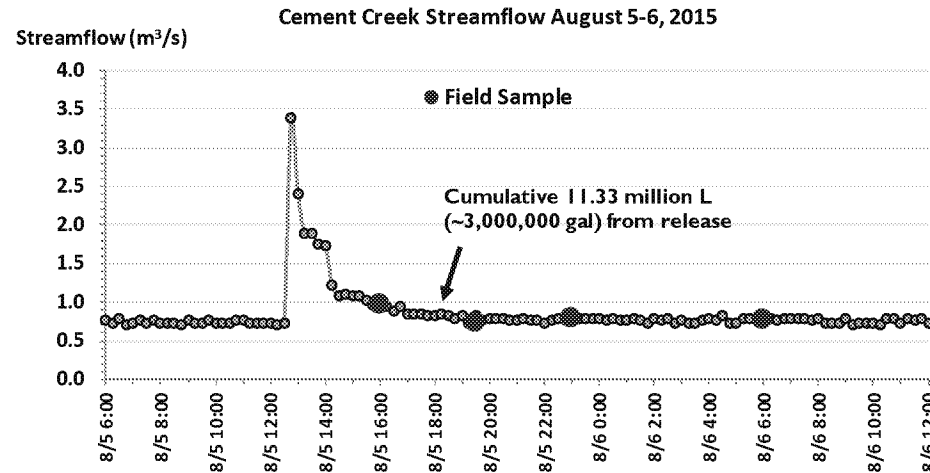
## Setting for the Gold King Mine Release

- The Gold King Mine (GKM) is one of hundreds of abandoned mines in this area of SW Colorado
- GKM is among the top 80 candidates for remediation to reduce acid mine drainage in the headwaters of the Animas River according to the USGS study of the area
- During preliminary remediation work on August 5, 2015, the closed mine entrance was accidentally breached
- An unexpectedly large volume of low pH, metals-laden water was released into Cement Creek



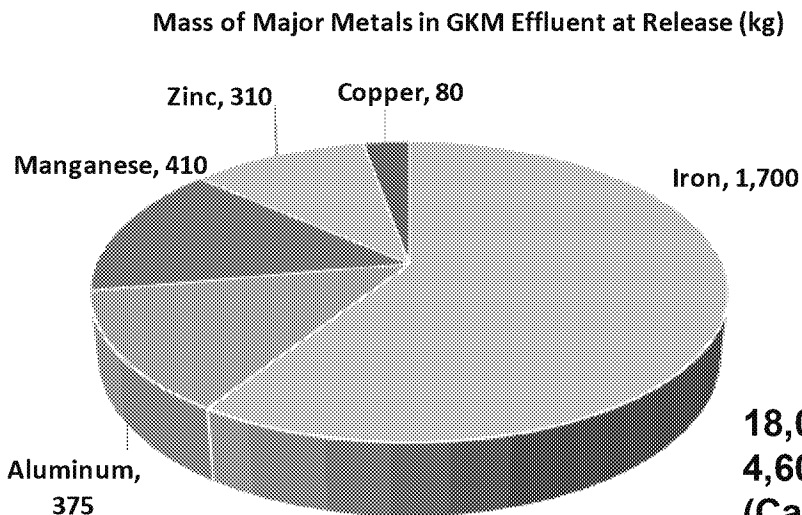
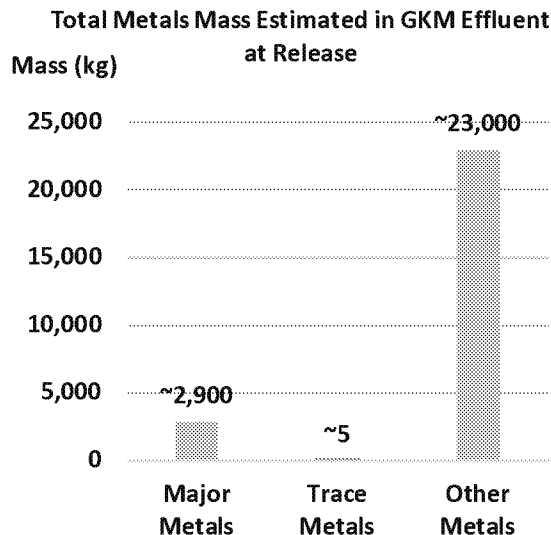
## The flood of acidic water from the release was measured by the USGS gage in Cement Creek

- The mine is located about 14 km (~9 mi) from the confluence with the Animas River in Silverton
- The released volume was readily determined from the USGS gage in Cement Creek
- Approximately 3,000,000 gallons (11.2 million liters) flowed out of the mine over a 7-hour period—most in the first 4 hours
- This slug of water and metals was observed and measured for hundreds of kilometers downstream



# The Metals Mass Released from the Gold King Mine

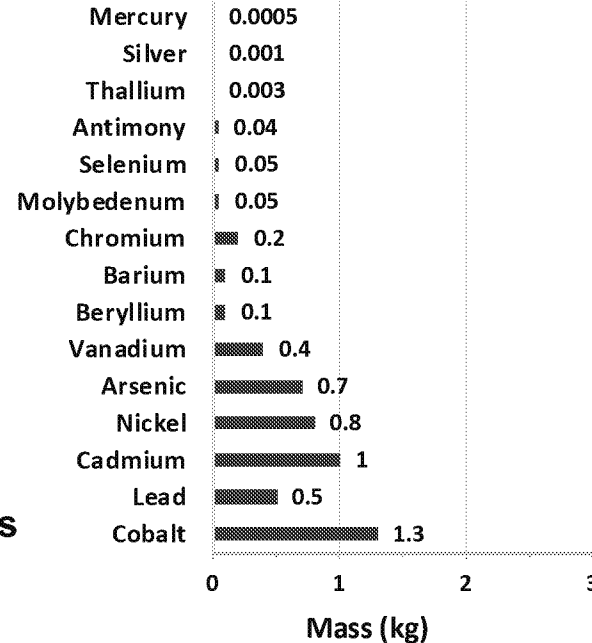
What was  
in the mine  
water?



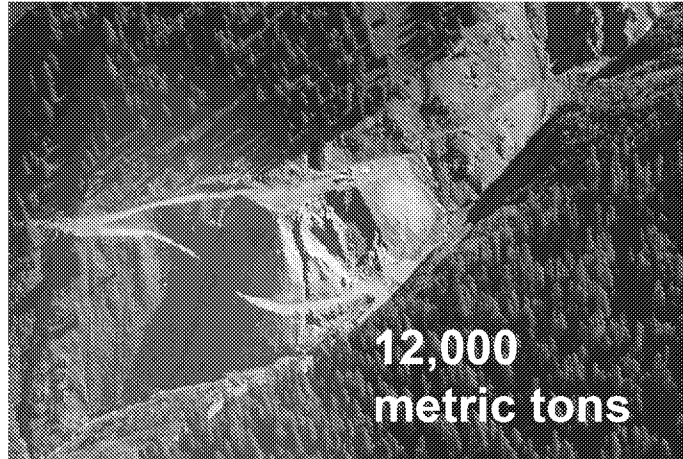
In the mine,  
metals were  
almost  
exclusively  
dissolved in  
water with pH  
=2.9

18,000 kg sulfate  
4,600 kg major cations  
(Ca, Mg, K, Na)

**Mass of Trace Metals in GKM Effluent at Release (kg)**



## The real story of the release was the erosion of the waste pile outside the mine



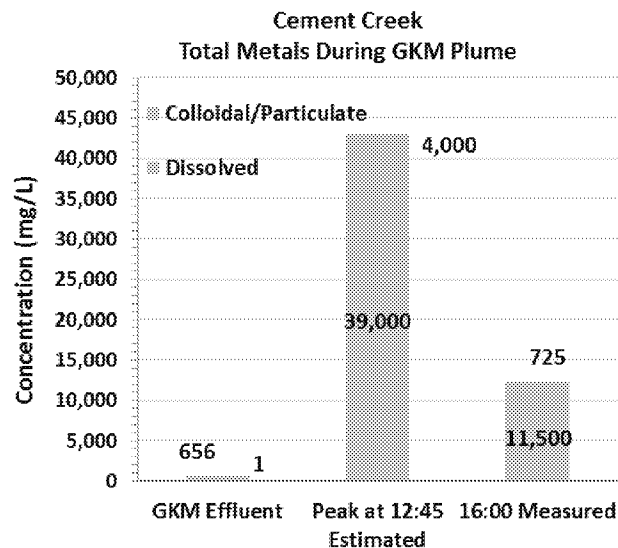
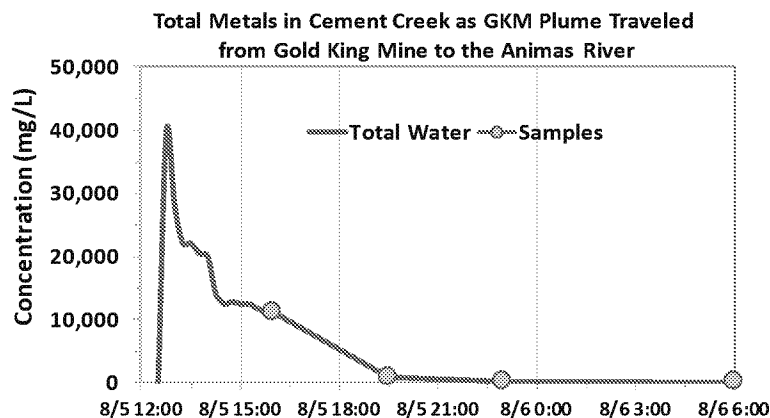
A considerable mass of additional contaminated mine waste was entrained by the rushing water outside of the mine and in Cement Creek



The entrained material was a mixture of particulate, sediment-bound, mineralized metals and inert “country rock” sediments

## GKM Mass Delivered to the Animas River

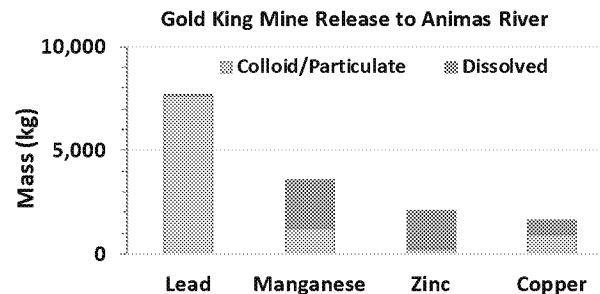
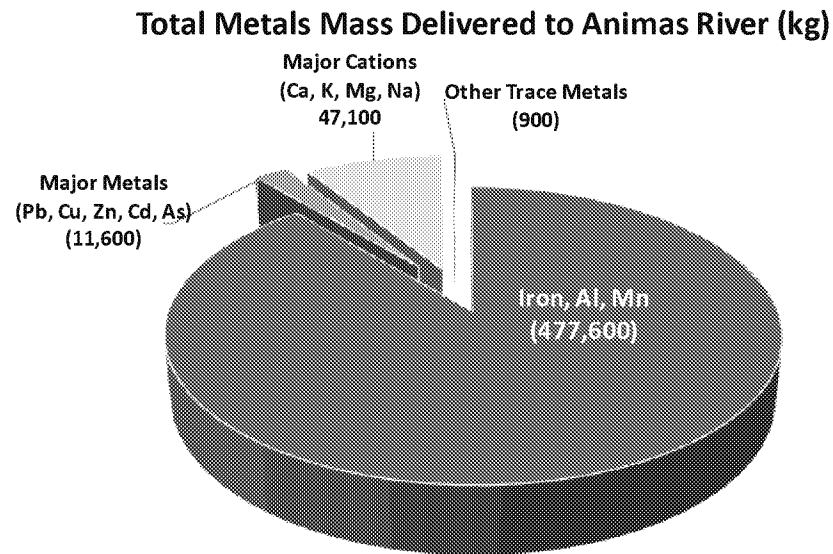
### Estimated Concentrations



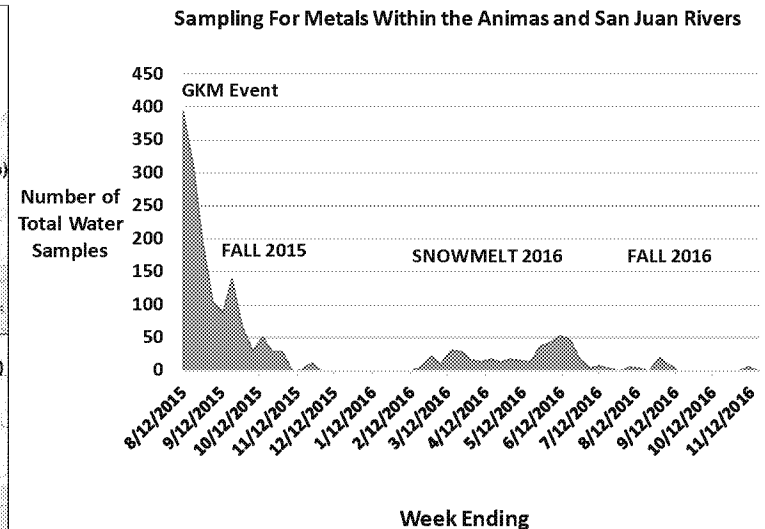
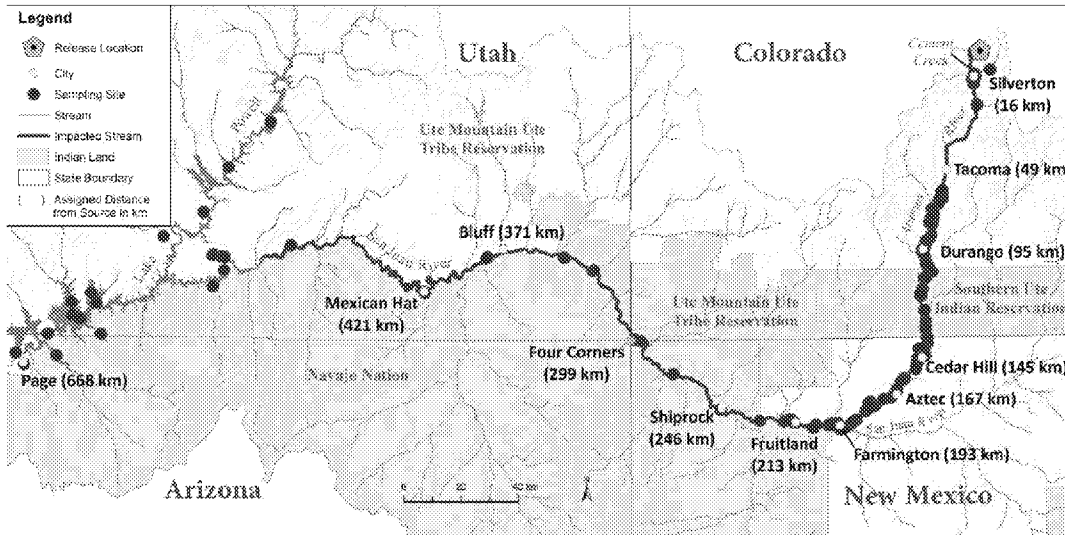
**Estimated Mass Delivered to the Animas: 490,000 kg**

**Colloidal/particulate: 475,000 kg**

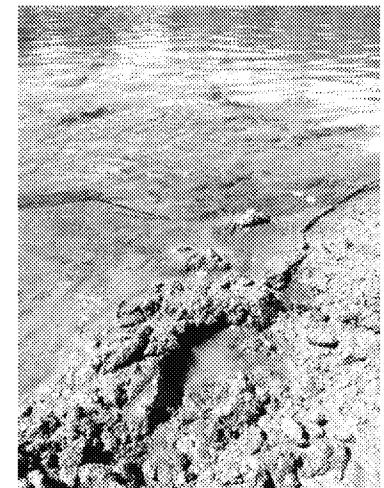
**Dissolved: 15,000 kg**



# Path of GKM release and sampling



- 310 sampling locations where one or more samples were collected
- EPA, states, tribes, NGO's
- Sampling began during GKM plume and continued at some locations through Fall 2016
- 1,900 water and 990 sediment samples







## The GKM plume traveled as coherent unit through the entire Animas and San Juan River system

The plume was initially a highly acidic solution with high concentrations of particulate and dissolved metals

It traveled at an average speed of 3.2 km per hour (2 mph) and reached Lake Powell 550 km downstream in approximately 7 days

The plume had a sharp front, highly concentrated inner core that passed quickly, followed by a low concentration tail that could be observed for days

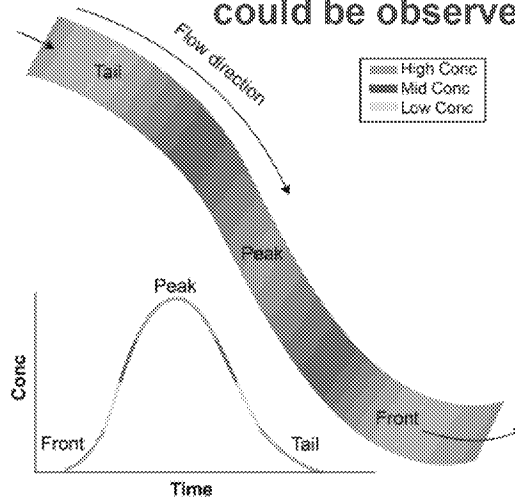


Photo: Bruce Gordon EcoFlight

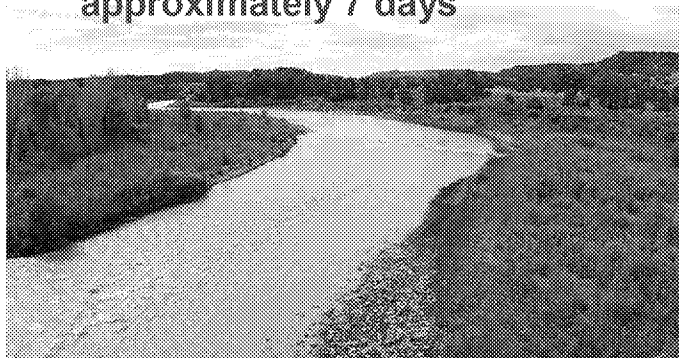


Photo: Southern Ute Indian Tribe



Aug 6

Aug 8

Aug 13

Aug 18

Colorado Department of Public Health and Environment

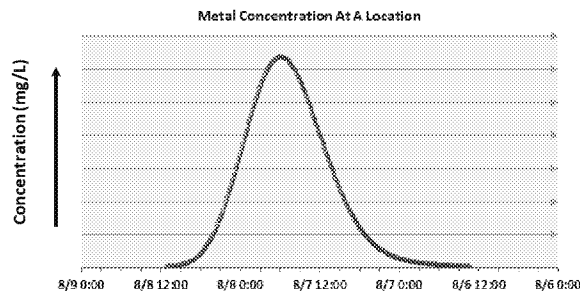
**The concentrations of metals was constantly changing within the plume—no two places saw exactly the same plume**



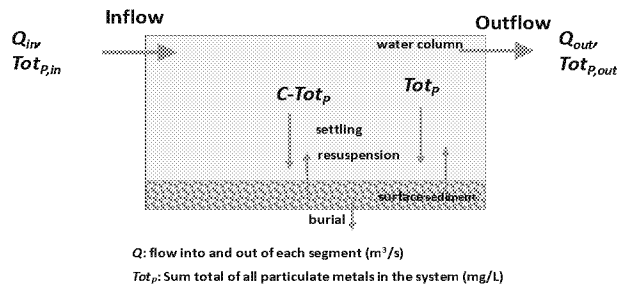
To quantify the GKM plume, we combined empirical analysis of samples with a water quality model that simulated its movement through 550 km of river

## Method 1

### Water Analysis Simulation Program (WASP)



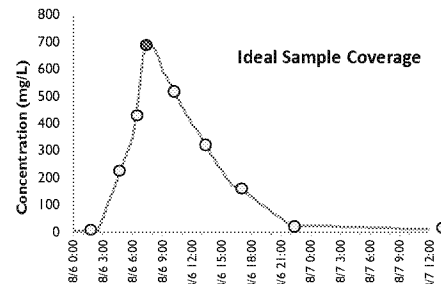
Applies physical process modeling to hydraulics of flow, partitioning mass between the water and streambed



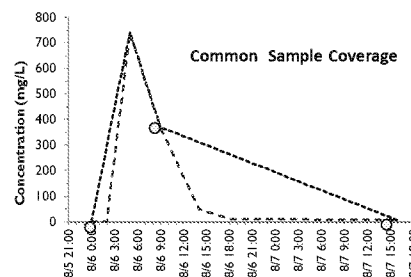
2-km segments

## Method 2

### Empirical Analysis of Observed Water Samples



Fit a concentration trace to observed water concentration, interpolating between

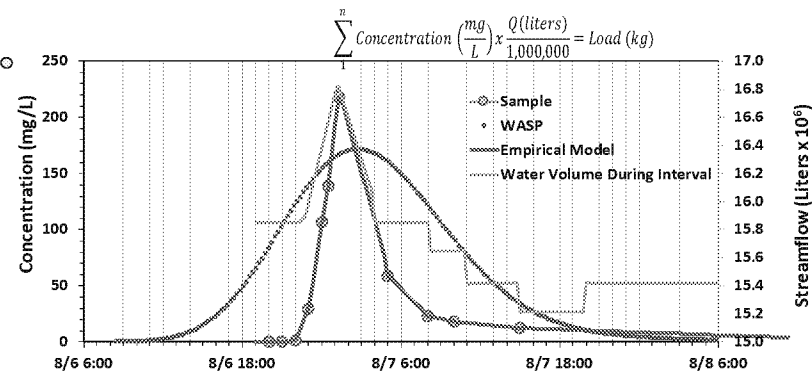


12 locations

## Analysis Goal:

- Replicate metal concentrations
- Compute mass load
- Quantify mass of material deposited

Gold King Plume at Durango, CO (RK 95)

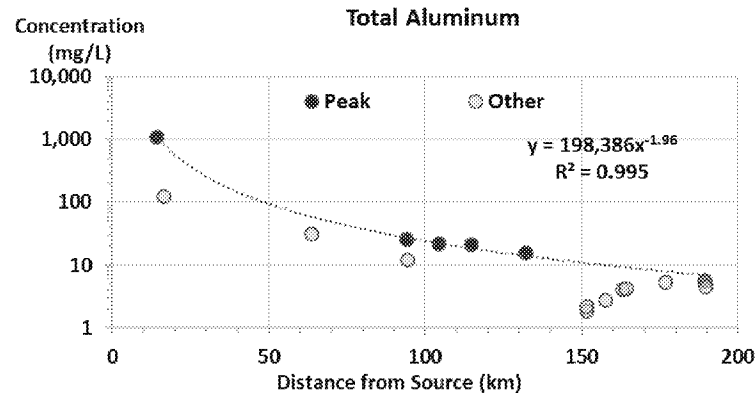


--Flow obtained from nearest USGS gages

--Concentrations estimated in 12- to 15-minute intervals

Dilution, deposition, and chemical reactions caused concentrations of dissolved and colloidal/particulate metals to decrease as the GKM plume traveled

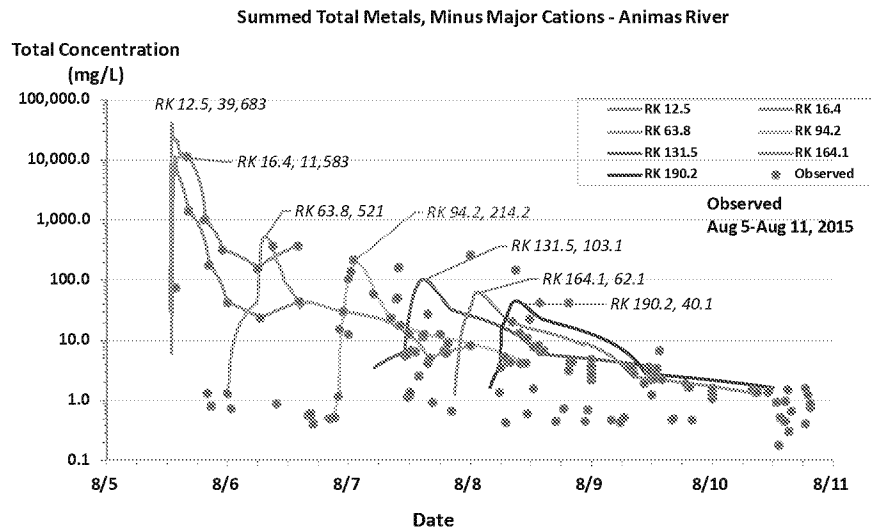
Samples near  
plume peak



Only 6 samples timed at  
or close to peak

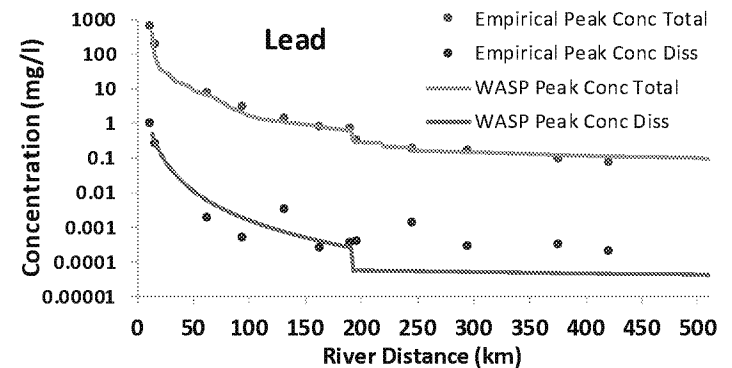
Almost all metals of interest  
follow this pattern

## Empirically modeled plume and water samples



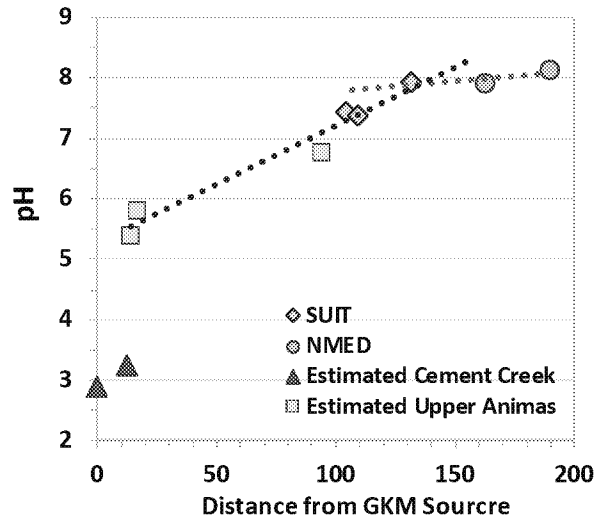
Peak summed water concentrations declined more than 3 orders of magnitude as the GKM plume flowed through the Animas River

## Modeled Peak Concentrations



# Concentrations and mass of metals were affected by various processes as the GKM plume moved: **Neutralization of Acidity**

**pH at Peak of Gold King Plume**

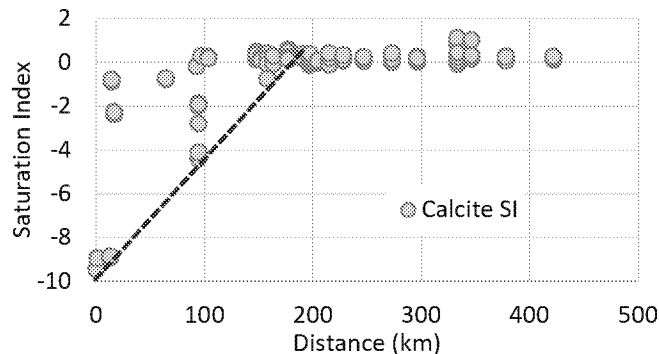


- Iron and Aluminum (hydr)oxides and other incipient minerals formed
- Yellow color intensified as neutralization proceeded indicative of Fe and Al (hydr)oxides
- 15,000 kg of dissolved major and trace metals precipitated into minerals

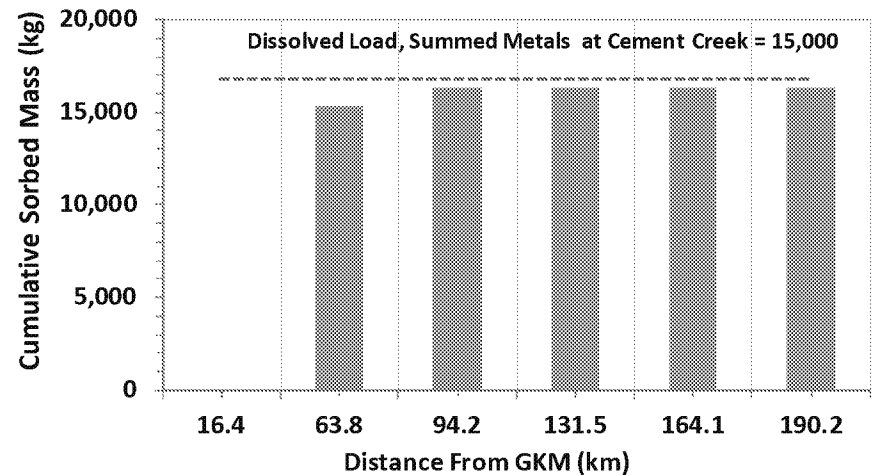


Photo: Mor, cCC BY – NC 2.0

**Distance to Neutralize Acidity Indicated by Saturation with Calcite**



**Sorption of Dissolved Metals**



# Deposition

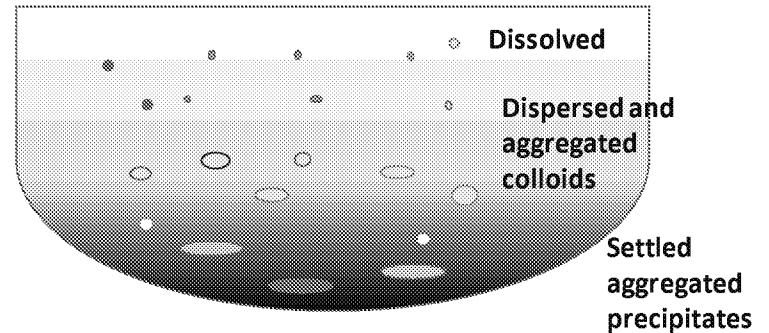
## Materials sourced from:

- Contaminated soils outside Gold King Mine and hillslope between mine and Cement Creek
- Scoured from Cement Creek
- Aggregated colloidal matter created from dissolved metals in the mine effluent

## Sediment in transport a mixture:

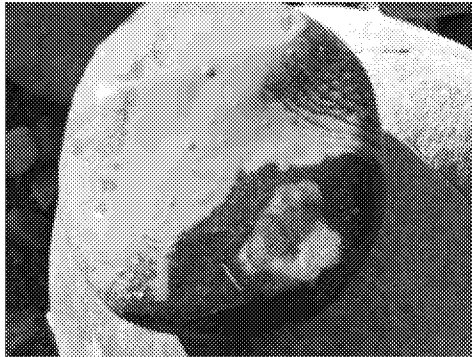
- Larger particulates (sand/silt)
- Fine particulates (clay)
- Aggregated colloidal precipitates of varying size, texture, and stability
- Sludge-like

## Partitioning- a function of pH, metal species, time

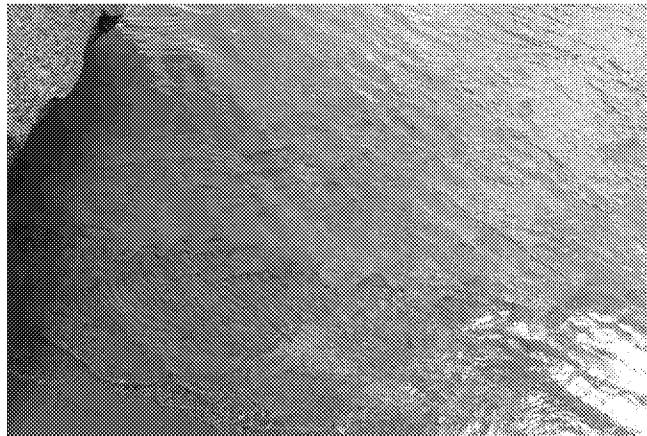
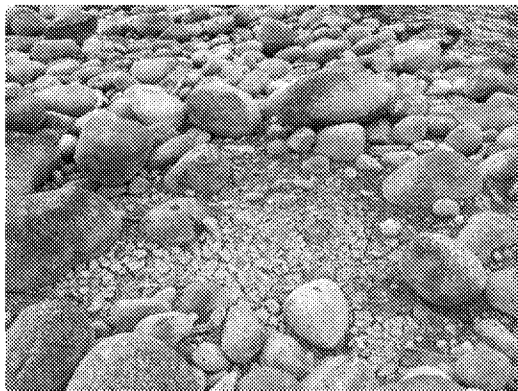


## In the streambed metals:

- bind to surfaces of rocks, sand grains, and clay
- become entrapped by microbes
- may be biologically taken up or released

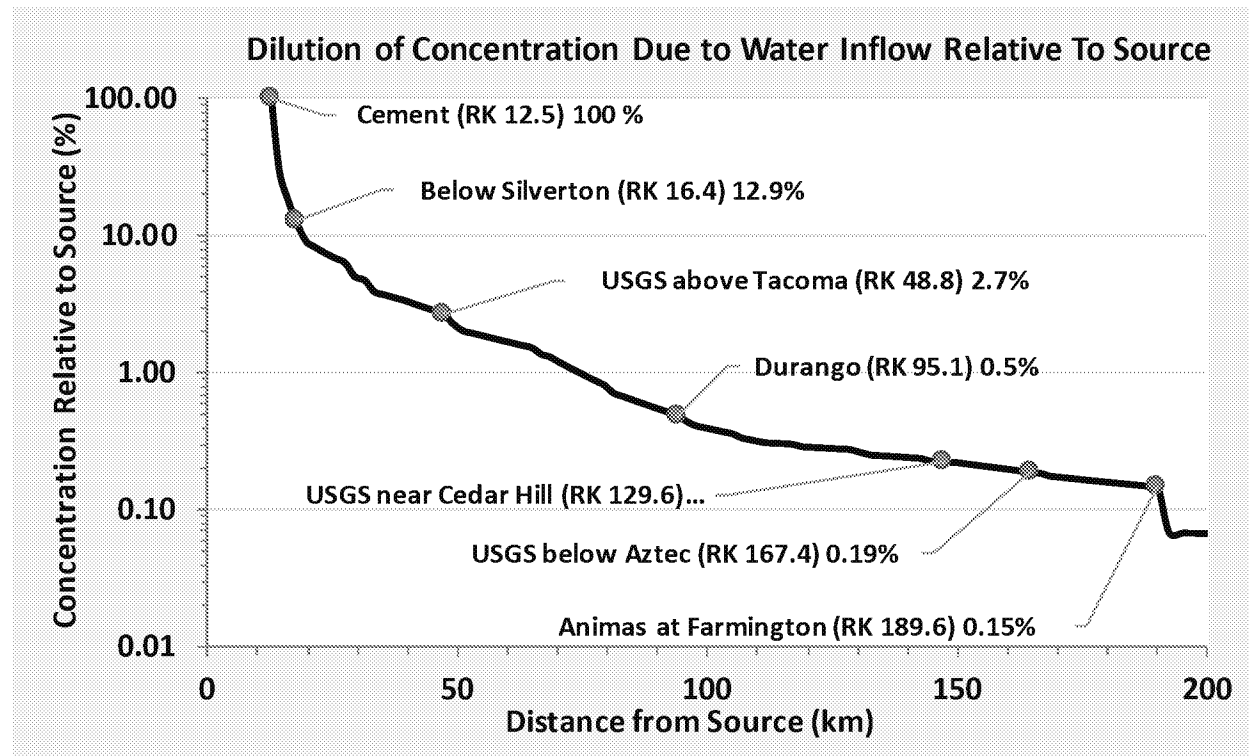


Colloids are fine solid particles suspended in a liquid, e.g. milk or paint



## Concentrations and mass of metals were affected by various processes as the GKM plume moved: **Dilution**

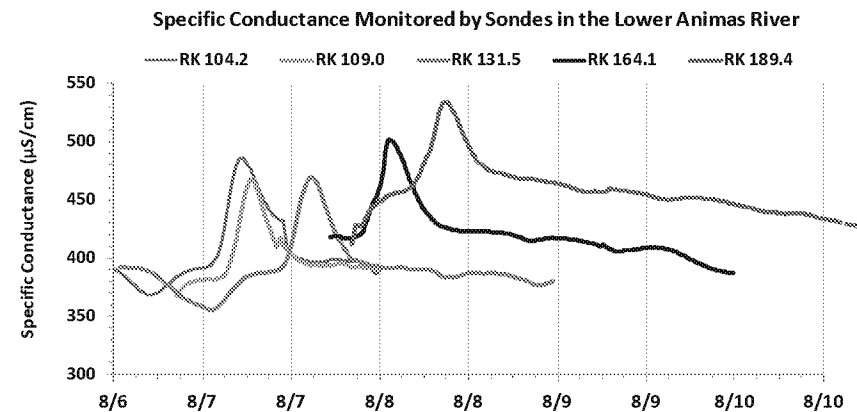
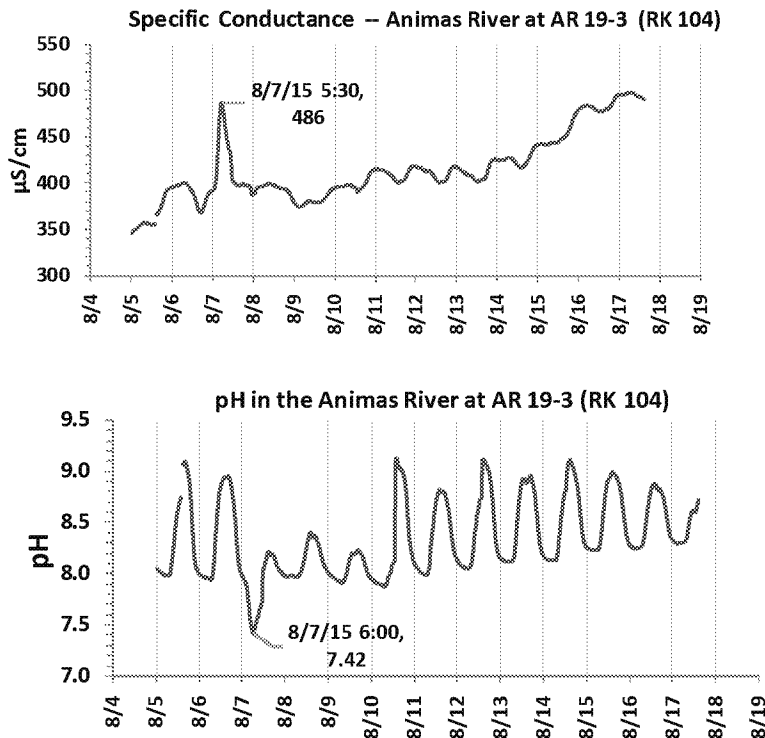
- As the GKM plume traveled, the release volume was mixed into the waters of the Animas and San Juan Rivers that contained much lower concentrations of metals.
- Flow increased from 122 cfs in the Animas above Cement Creek to 2,860 cfs in the San Juan at Bluff, Utah
- Significant dilution of the release mixture occurred by the time the plume passed Silverton





**Most of the metals mass released from GKM moved in a highly concentrated core with a duration of about 12 hours**

**Continuously measuring sondes helped establish internal characteristics of the plume**

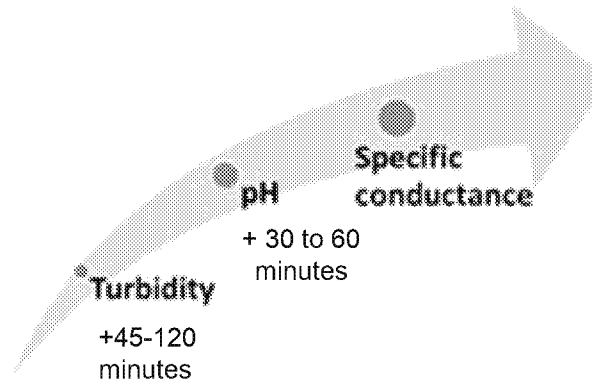


**Sonde parameters showed that the GKM plume traveled in a very tight profile**

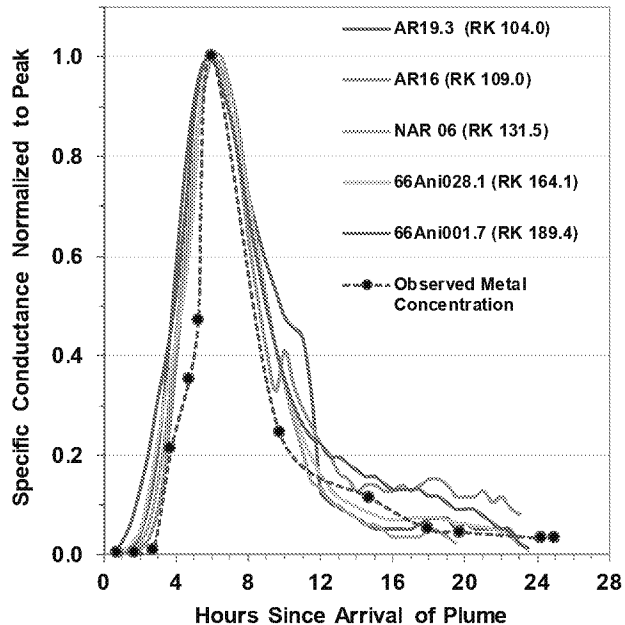
**The plume maintained a remarkably consistent shape over a long distance with very little dispersion of the core**

# Internal characteristics of the Gold King Plume

**Individual sonde parameters systematically peaked at different times**

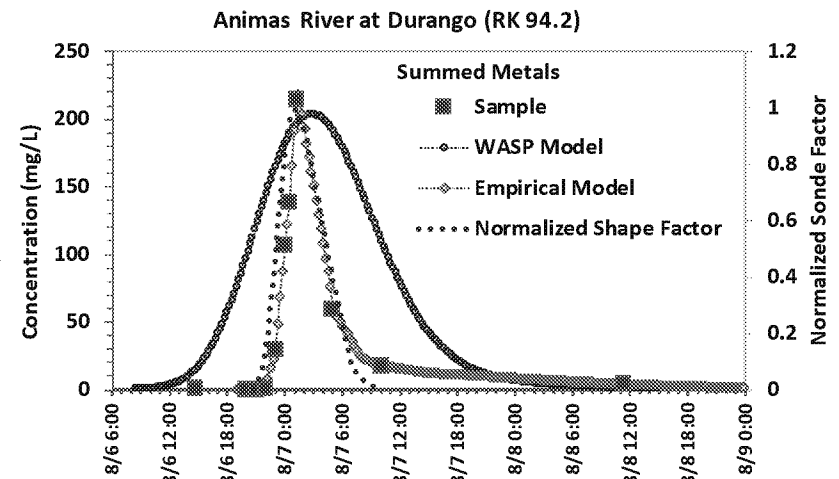


**Sonde Plume Shape Factor**



**Shape Factor: Normalized to Peak**

**Metals concentrations followed the specific conductance "shape" closely**





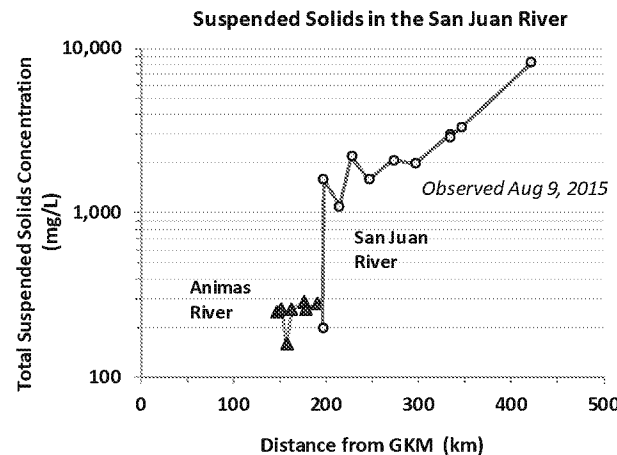


## The Gold King Mine plume as it entered the San Juan River

- The San Juan River had high sediment loads during passage of the GKM plume
- Sediment provides another source of metals
- At the same time, concentrations in the plume were relatively low
- Strong visual and measured signal lost due to sediment associated metals
- The San Juan doubled the flow and further diluted the plume

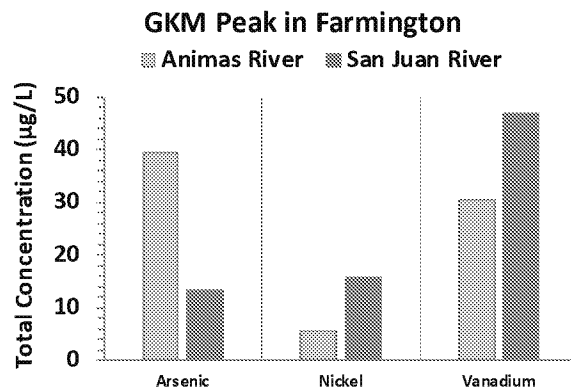
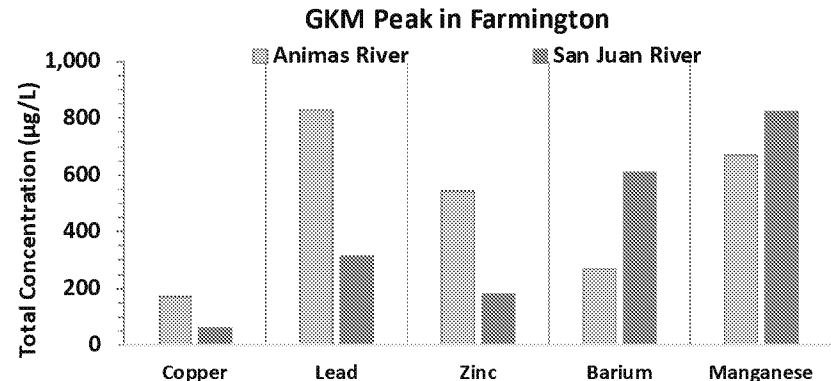
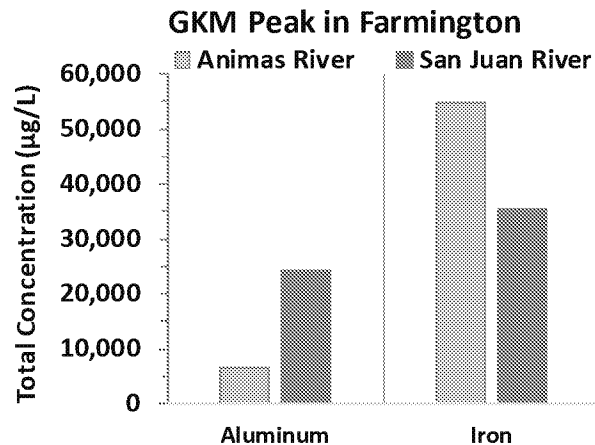


Confluence of Animas and San Juan as GKM plume passed through (RK 191)



San Juan River in Utah during the GKM plume

## Comparison of concentrations in the Animas and San Juan Rivers at the GKM plume peak shows metals more comparable



- No dissolved metals from the GKM release were delivered to the San Juan
- Sediment naturally contains metals
- Some metals were higher in the Animas than the San Juan during the plume

Lead, Copper, Iron, Arsenic

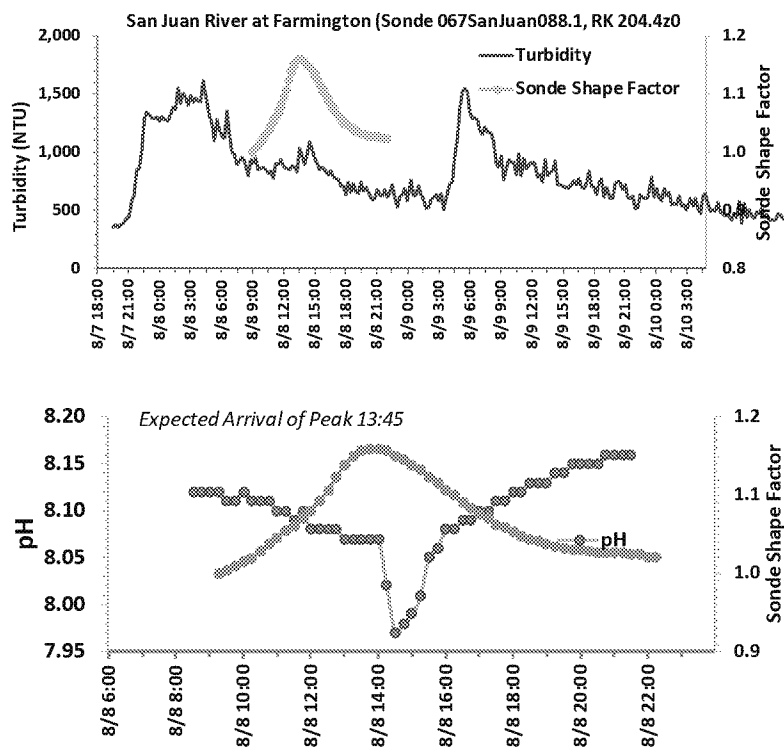
- Some were higher in the San Juan

Aluminum, Barium, Manganese

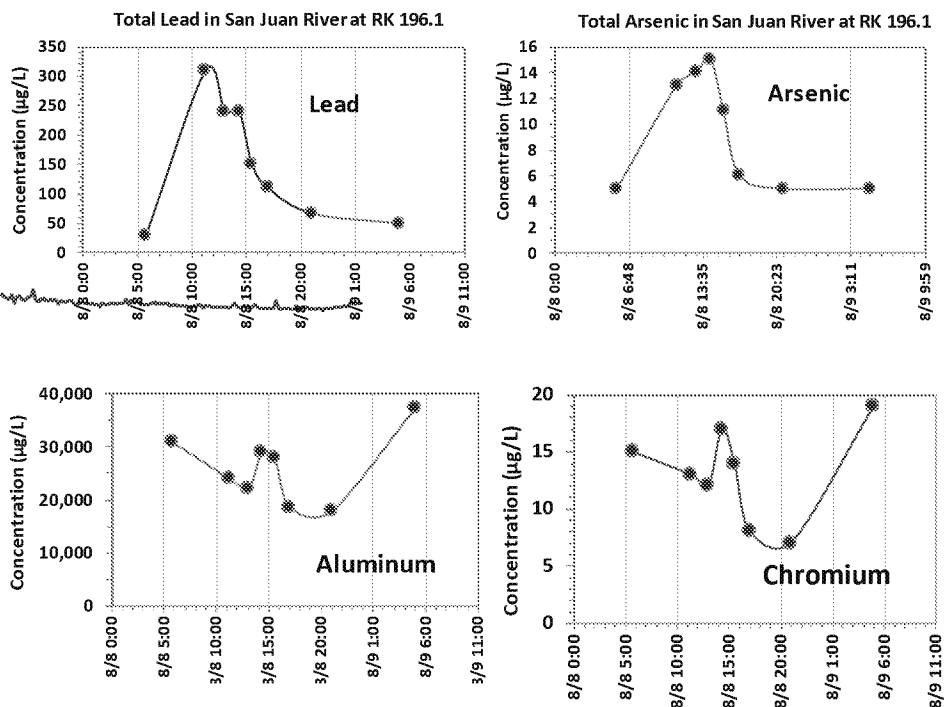
The combination of relatively low concentration of metals in the GKM plume at this point and the additional metals from the San Juan sediments made it much more challenging to isolate and quantify the plume.

# Metal Concentrations in San Juan River During GKM Plume at RK 196 in Farmington

Continuous sonde at RK 204 shows GKM in relation to background sediment



Metals Concentrations



Note: we combined measurements at two sites accounting for travel time to produce these graphs

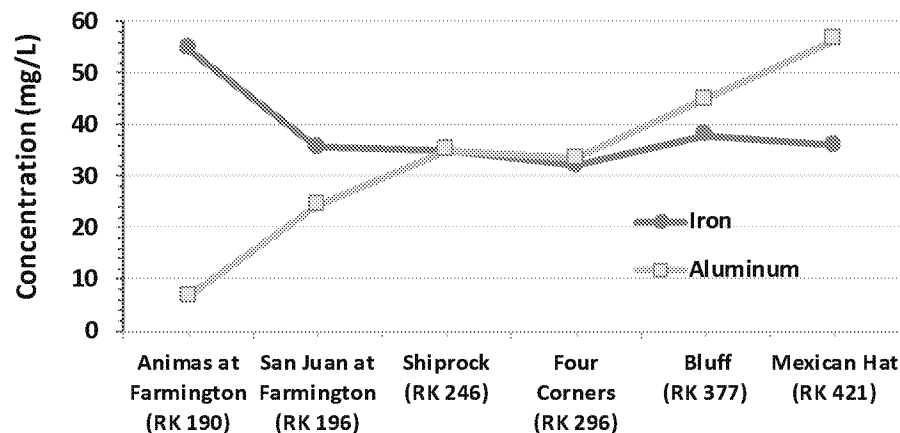
Metals were elevated within the background during a 4 to 12 hour period at the expected arrival time of the GKM plume

## GKM peak concentrations in the San Juan River

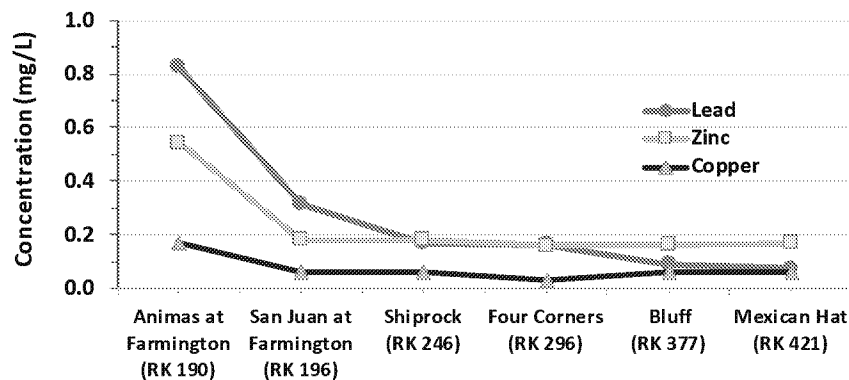
Total concentrations of metals due to GKM at peak generally remained constant or declined through the San Juan

The Aluminum and lead levels exceeded some Navajo Nation and Ute Mountain Ute water quality criteria for domestic water use and agriculture

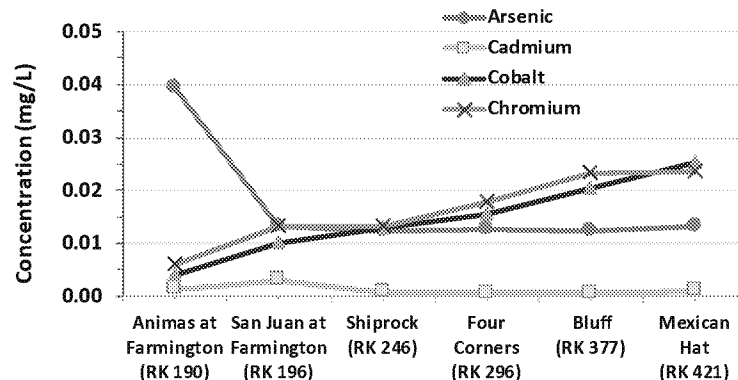
Total Metals Due to GKM at Plume Peak



Total Metals Due to GKM at Plume Peak

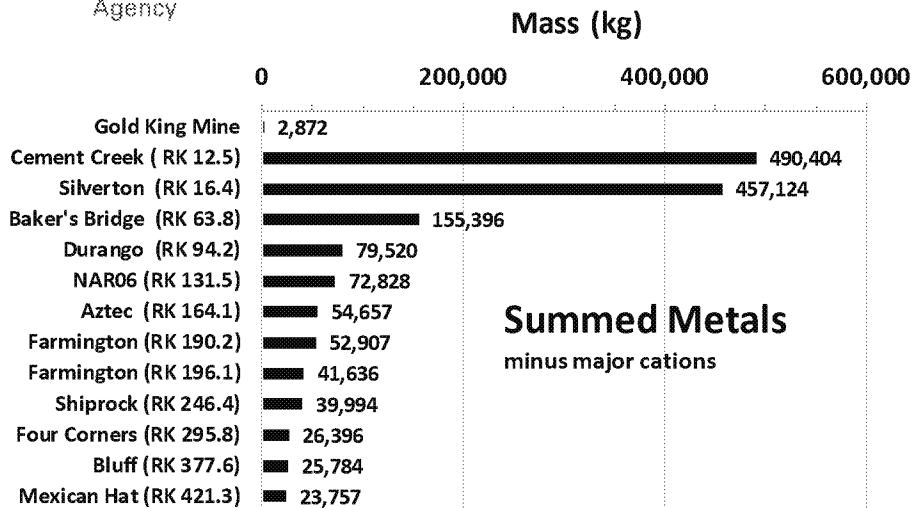


Total Metals Due to GKM Plume at Peak



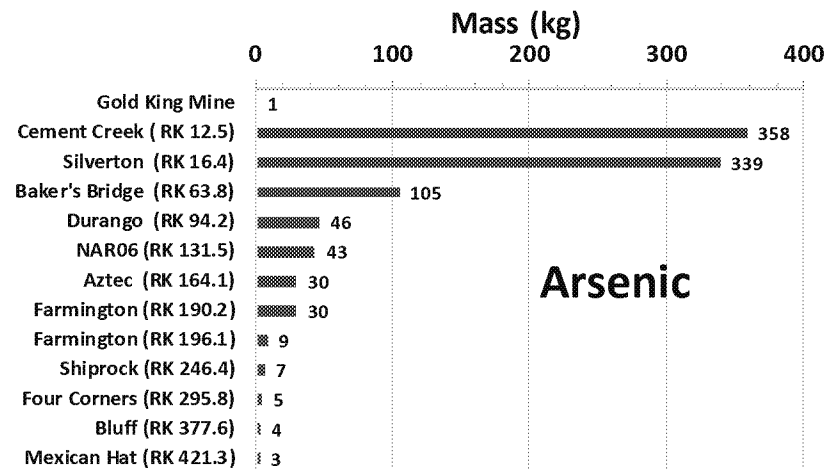
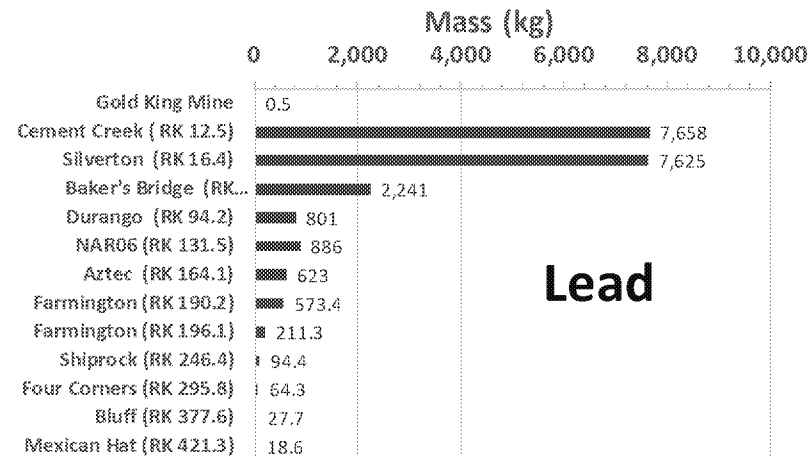
# GKM Plume Mass Accounting

## Mass Transport During the GKM Release Plume (kg)



<sup>1</sup>excludes major cations

The GKM plume delivered about 24,000 (up to 45,000) kg of metals to Lake Powell. The remaining 465,000 kg were deposited in the Animas and San Juan Rivers.





## Summary of Gold King Mine Plume

- **The Gold King release was initially a highly concentrated mass of particulate/colloidal and dissolved that migrated through the system as a concentrated “plume” of material**
- **Most of the material came from the waste pile outside the mine—not from within it.**
- **The most noteworthy contaminants were lead, and to a lesser extent, arsenic**
- **Various physical and chemical processes worked on the release plume reducing its acidity, and transforming the dissolved fraction to solids while incorporating them into minerals such as iron and aluminum (hydr)oxides**
- **The concentrations of metals declined significantly as the plume moved due to dilution and deposition**
- **90% of these solids deposited before the GKM plume reached Lake Powell, with 80% left in the Animas River upstream of Durango**
- **Lead and aluminum criteria for agricultural and domestic water use were exceeded in some locations during passage of all or part of the plume.**